Forecasting Research

Forecasting Research Division
Technical Report No. 193

Proposals for work on wake vortices for the remainder of 1996 and brief thoughts on possible work during 1997.

by

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May 1996

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0. Introduction.

When aircraft are generating lift, trailing vortices are formed at each wing tip. These vortices then tend to drift apart at a rate of around 5 knots and are induced downwards by their mutual effect i.e. that the rotation of each vortex is in an opposite direction, leading to a downward component on the side of each vortex nearest to the other.

Individual vortices can cause roll and subsequent loss of control, in addition the downward component can cause loss of altitude. The strength and track of these vortices in time is the main study area and there are considerable uncertainties and approximations, particularly in the boundary layer where the frictional effects of the surface are important.

The overall task is to attempt to demonstrate that aircraft can, on occasions, safely be allowed to follow each other more closely. A reviewing process began in November 1995, involving both literature reviews and consultations with the most active players in the subject.

Four anemometers are to be installed at Heathrow airport in the summer of 1996 for ATC purposes and it is hoped that information from these will enable the basis of a "vortex advisory system" to be devised.

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1. Information gathered to date.

Much of the work done to date has involved familiarisation with the problems involved in allowing some relaxation to the rather cautious separations that are used in aviation owing to the hazards caused by wake vortices. There has been a great deal of published material dating back to around 1970 that covers the many different aspects and disciplines that need consideration. These disciplines include boundary layer meteorology, mathematical modelling, fluid dynamics, instrumentation for both meteorological and vortex observation, and aviation practices and restrictions.

1. 1. Boundary layer meteorology.

This is the most relevant area to the work that the Meteorological Office can expect to become involved in. Essentially wake vortices are created whenever an aircraft is generating lift and hazards exist when such a vortex remains in the flight path of a following aircraft for a sufficient time and at a sufficient intensity to cause upset to the following aircraft as it encounters the wake. Boundary layer meteorology is clearly the most important area of concern since any such encounter will be most critical when the following aircraft is within a short distance of the ground so that any recovery action may not be possible should a low level encounter occur.

Vortices can be removed as a threat by two mechanisms. Firstly the crosswind component (winds normal to the flightpath of the following aircraft) will essentially move the vortices bodily out of the path of the following aircraft. Secondly, the levels of turbulence in the atmosphere that are thought to be the main mechanism for causing a decay of vortex strength and in time will allow such a vortex to become non-hazardous.

1. 1. 1. Crosswind transportation of vortices.

Some considerable work has been done in the past to establish what level of crosswind component would be sufficient to remove any vortices from the path of a following aircraft. The initial reaction has been to assume that vortices are transported at the same rate as the crosswind velocity[1]. This idea has led to the thought that if the crosswind component of the wind can be predicted with a high level of accuracy over short periods of up to 20 minutes, then the transport of vortices can be also predicted. Unfortunately, many attempts have been made to give such a prediction with only limited success[2]. Firstly, the required crosswind components can be estimated, leading to values of the order of 6 knots. Forecast error then needs to be incorporated, which means that up to 4 knots needs to be added to that value to account for both spatial and temporal variations in wind velocity. A crosswind component of 10 knots does not occur frequently at most airports and certainly not at Heathrow, which is the site that is of concern to this work. Secondly, the motion of vortices has been found to differ from advection by crosswind velocities. In fact there are vertical motions that tend to cause a tilting of a vortex pair that increases the motion of one vortex

and decreases the speed of motion of the other[3]. This leads to more complex calculations regarding the required crosswind. This has been done to a degree[4], although the resulting calculation results in a required crosswind of 9 knots which includes allowance for forecast error. This estimate is discussed in more detail in section 5 of this paper.

1. 1. 2. Vortex decay, caused by turbulence ?

It is widely believed and demonstrated[5] that levels of atmospheric turbulence do influence the hazardous lifetime of a wake vortex. Problems have been encountered in modelling this and in finding a suitable turbulence parameter that can be correlated against vortex lifetime from vortex measurement experiments. Much of the work to date on this has been carried out by non-meteorologists with various turbulence measures being estimated. RMS. turbulence, the standard deviation of short-period mean wind speed, is influenced by synoptic changes and gives no certain indication of the level of stability in the atmosphere. The turbulent dissipation rate (ε) is a measure of small-scale turbulence that is thought to play an important role in vortex decay. Unfortunately, this parameter is difficult to estimate with various functions having been tried:

$$\varepsilon = windspeed * cons\tan t$$

$$\varepsilon = F\left(windspeed^{1/3}\right)$$

In reality, ε depends on far more than wind speed alone and other parameters do need consideration. ε can be estimated albeit with rather limited accuracy on most occasions[6]. The two estimates above have not produced good correlation figures with measured vortex decay with the more sophisticated method yet to be attempted.

Reasonable correlation figures have been obtained using Pasquill stability and both the vortex lifetime and vortex strength after a fixed time. This is encouraging as this parameter is essentially a crude representation of what the more sophisticated estimate of ε seeks to do.

1. 2. Fluid dynamics and mathematical modelling.

The next set of problems involves the reaction of aircraft as they encounter a wake vortex and the differing properties of the vortices depending on the type of generating aircraft. Given that both of these problems are not at all trivial, the ultimate aim is to produce and use a model to describe the formation of vortices and their subsequent effect on following aircraft of whatever type. The models already mentioned above in estimating ε can be used as input to such models.

1. 2. 1. Vortex generation.

It is again well known that the initial and subsequent strength of a vortex pair are directly

proportional to the weight of the generating aircraft, although it has more recently been agreed that it is actually the wingspan that is of more significance (these parameters are highly dependent on each other and can be reasonably substituted for each other in most cases). Values of initial vortex strength are readily available; vortex strength can be measured in terms of either tangential velocity, or more frequently in terms of vorticity or circulation. These values have been estimated by fluid dynamicists and have been verified to a certain extent by observation, principally in the USA, although again much, if not all, of these data remains unpublished.

1. 2. 2. Vortex decay and transportation models.

This is an area that has proved very difficult, and most experts seem to agree that no entirely satisfactory model has been developed as yet. Having said that, several attempts have been made. These models use meteorological parameters as input variables as well as the parameters describing the particular generating aircraft as discussed in the previous section. Two main types of model have emerged; firstly a model was devised that took rather unsatisfactory meteorological parameters and used known methods of vortex decay, Crow instability, vortex bursting and general decay by small-scale turbulence[7]. A problem with this model is that it does not strictly apply in areas close to the ground (when the vortices are said to be in ground effect). Work has been done to remedy this in France although this work has not been formally published as yet.

Observations of vortex strength show that the strength (τ) tends to remain fairly constant for a rather variable time before an almost exponential decay begins. This observed decay pattern is not predicted by such models as described, and so a more empirical model has been derived that simply mimics actual observed decay patterns by Hallock in the USA[8].

A further research project was set up a few years ago in India with the view that addressing the problem from a purely fluid dynamics standpoint would perhaps be more likely to produce a reliable model[9]. This work has not produced any results that are significantly different to those produced by[7].

1. 2. 3. Vortex effect on encountering aircraft.

The most recent work in this field has been performed by Woodfield although again this work has yet to be published. A model has been created that takes vortex circulation and strength from models described in the previous section. The resulting calculations give estimates of maximum roll, height loss and pitch for the encountering aircraft. The results are used on a statistical basis, which is reasonable since the multiplicity of variables and estimates of many of them prevent any greater reliance being placed on the results. The statistics are interesting though as all possible encounter angles and speeds can be assessed to give an idea of a worst case, and under what circumstances those cases would arise. This naturally leads to the possibility of estimating the probability of worst case situations arising.

1. 3. Vortex measurement and observation.

Theoretical models and calculations need to be checked with reality to ensure consistency. This is vital to all research activities but is expensive and difficult in the case of wake vortex research as the measurement process must not present a hazard to landing/departing aircraft but still needs to be close enough to be able to observe the required phenomena, whether it be the vortices themselves or the prevailing meteorological conditions.

Careful consideration needs to be given to the results of any observational studies to ensure that the measurement processes themselves are appropriate and meaningful with regard to all of the disciplines involved. It is not very useful to have superb measurements of vortex tracks and strengths if the corresponding meteorological conditions have not been observed adequately.

1. 3. 1. Modern measurements of vortex motion and behaviour.

Instrumentation over recent years has improved to the extent that accurate measurement of vortex strength and motion is now relatively straightforward[3]. Much work has again been carried out in the USA, largely with the involvement of Hallock although this has not been analysed to the extent that it can be published. One important piece of published work was produced in the UK in 1995[10]. This work has proved useful with regard to the verification of model prediction and of estimates of aircraft parameters, as well as simply gaining experience in general vortex motion and decay under various meteorological conditions. The measurements involved use Doppler radar equipment and/or laser equipment These measurements involve the application of the Doppler principle to either conventional radar wavelengths or the shorter laser wavelengths.

1. 3. 2. Older observational data.

Less sophisticated data using lines of anemometers to detect vortices are in existence in the U.S.A and are expected in the public domain in the near future. Once these data are published much information will be of use especially bearing in mind the sheer volume of almost 100,000 observed vortices. This information will be of use with regard to model verification once again, but also with regard to hazard definition i.e. how strong does a vortex need to be after, say, 60 seconds to constitute a hazard. This leads to the study of known incidents.

1. 3. 3. UK, CAA wake vortex database.

Since around 1972 the UK Civil Aviation Authority (CAA) have operated a wake vortex incident database. This database contains report information from pilots that are requested in the event of a wake vortex encounter. A good deal of complementary information is also included such as information from the vortex generating aircraft, weather conditions, and radar/flight recorder information.

This database is the only one of its kind and has reports covering more than 20 years and several thousand reports. The majority of these, around 75% are concerned with approach or departure from Heathrow with a high percentage of these also containing the relevant meteorological information. The reports cover all altitudes but a significant proportion, around 40% are at altitudes of less than 1000 feet and are therefore of interest as potentially hazardous situations.

Information gleaned from this database has been published annually but a more rigorous publication was presented in 1991[11]. The information that is currently produced annually is of great interest to research effort from the point of view of hazard definition (these incidents can be thought of as being evidence of hazard), but the meteorological information has not been used to any great extent. The only information that has been published is in the form of frequency distributions of incidents against crosswind strength.

1. 4. Aviation practices and consequent restrictions.

Any theoretical results that are put forward regarding wake vortices and the level of safety that is required, need to be consistent with other restrictions applied to aircraft separation for unrelated reasons.

1. 4. 1. General regulations.

Internationally accepted regulations are applied on a world-wide basis with regard to wake vortices. These come mainly in the form of required separation distances. In order to do this all aircraft are categorised into three groups by weight. Separation distances are then given that apply to the various combinations of aircraft from these groups. The principles involved are simply that a larger aircraft will generate a stronger vortex and that a smaller following aircraft will be affected more strongly by a vortex of the same strength than will a larger aircraft. Separation distances range from 3 miles to 6 miles depending on the particular combination of aircraft involved.

There are local differences that are applied to these regulations. These are, without exception, differences that are more conservative; in other words they all err on the side of caution. The UK system uses four groups across the country as does the current US system although the groupings do not entirely coincide. Some trials have been carried out at Heathrow and Gatwick in recent years using five groups. There is a proposal to experiment with six groups at Heathrow although this thought has to be tempered by the fact that it will create an extra workload on ATC in that they will have to perform more complex calculations with these additional groups.

The ultimate idea of getting the best vortex separation criteria is to have a computerised system with every aircraft type placed in its own category although it is unlikely that such a system will materialise in the near future.

Theory would dictate that in certain meteorological circumstances vortex separation would be unnecessary, although reasonably large separations are still required owing to radar

usage and perhaps to poor visibility etc.

1. 4. 2. Pilot knowledge and training.

Many of the incidents that have been reported and investigated have clearly resulted from circumstances that could have been easily avoided and were independent of the prevailing meteorological conditions.

Key points are that aircraft should always endeavour to maintain the standardised separation distances, and perhaps more importantly that a following aircraft should endeavour to remain above the path of a preceding aircraft's path. Education packages have been published by the CAA but the most comprehensive package has been produced in the USA[12]. The immediate implications are that well informed ATC staff and pilots would have eliminated the great majority of vortex encounters that have been reported over the past twenty years.

1. 4. 3. Issues that relate specifically to Heathrow.

Heathrow has two parallel runways both aligned at 274°, because of noise restriction they are obliged to operate in segregated mode, i.e. landings on one runway and take-offs on the other. The implication of this is that there are numerous occasions where many aircraft are following close to each other and on the same ascent or descent paths thus allowing ample opportunity for wake vortices to cause a problem.

1. 4. 3. 1. Departures.

All departing aircraft will be using the same runway at any time. Vortex separation criteria do cause significant delays to waiting aircraft, particularly at busy times. One saving grace is that flight paths on departure can be arranged so that consecutive aircraft usually have diverging routes from a short distance beyond the end of the runway. Also, efforts can be made to optimise the order that aircraft depart, so that large aircraft do not immediately precede the smallest aircraft.

If conditions were found to be conducive to rapid vortex decay or transportation then ATC would require between 2 and 5 minutes notice in order to be able to prioritise the departure sequence. In other words, any forecast of wind conditions at the aircraft rotation point would have to be applicable in the range up to 5 minutes ahead. However a reliable forecast of two minutes would allow separation to be reduced when conditions allowed.

Vortices created by departing aircraft are strong because of the maximum weight often carried by these aircraft, although the faster take-off speed does counter this increase in vortex strength.

1. 4. 3. 2. Arrivals.

Arrivals at Heathrow arguably cause more problems since aircraft follow each other on very similar flight paths for a considerable distance before landing. Thus the opportunity of a wake vortex encounter is far greater than for departing aircraft. Owing to the large number of movements at Heathrow four holding areas are used with ATC having the difficult task of ordering the aircraft sequence for landing. These holding areas are around 15 minutes flight time from the airfield, and so any selection of aircraft order and separations for approach must be done up to 20 minutes ahead.

This twenty minutes requirement means that forecasts of wind conditions, and therefore of vortex decay, forecasts must be issued for periods of up to twenty minutes ahead.

Vortices created by landing aircraft are made stronger by the slow speed of the aircraft but this is tempered by the fact that any aircraft will be at its lowest weight upon arrival, which reduces the strength of its vortices.

1. 4. 3. 3. Capacity requirements.

There are proposals under review to build a fifth terminal at Heathrow, this together with constant pressure from the airlines mean that there will always be a considerable effort placed on increasing the runway capacities. Wake vortex separation criteria are the largest single restriction on that capacity.

A departures trial will be taking place during 1996, planned to start in March in which six vortex categories will be trialed and some airlines have volunteered to give their pilots a greater responsibility for vortex avoidance. This is being done by ATC clearing the aircraft with a warning issued that vortices could still be present, this clearance could be after as little as forty seconds after the previous departure .

2. Current research.

During the last week of January 1996 a three day meeting concerning wake vortices was held at CAA house in London with a visit to ATC Heathrow on one of the days. The attendees included US researchers as well as those from Germany and France.

2. 1. German work at Frankfurt.

The Germans are the first group to have a firm proposal to implement a vortex advisory system for operational use. This is likely later this year, although its scope is a little less ambitious than most attempted in the past, perhaps rightly so.

Frankfurt also has two parallel runways although these are only 500 metres apart. The two runways are both used for take-offs and landings simultaneously with the main problem being the risk of vortices transferring from one runway to the other. This means that vortex separations are currently required, not only for each runway approach/departure, but also between aircraft approaching alternate runways. This will be avoided hopefully by use of an advisory system.

Essentially they have used a confidence interval for the wind velocity that is then carried forward into vortex motion and decay modelling. Limits are given to the ATC via a computer terminal describing a length of time that confidence is above a certain level that vortices will not cross between runways.

There are some problems as to how a confidence interval can be applied in a safety case although a case has been presented that will be published in due course. Such an approach is worth bearing in mind, although the requirements for Heathrow will be more stringent.

2. 2. French work.

Two separate pieces of work have been, and are being carried out by the French with a view to setting up a scheme at Orly airport that has many similarities to the proposed work at Heathrow.

2. 2. 1. Proposals for work at Orly airport.

Four anemometers are to be set up at Orly airport, near Paris, in the next few months. These will be positioned in a similar fashion to those at Heathrow, i.e. at each end of the two parallel runways. The French intend to develop a vortex advisory system using advection techniques from these anemometers using mean speeds for periods as little as ten seconds.
They intend to advect these ten second mean speeds as forecast values for up to a minute.

2. 2. 2. Mathematical modelling in Toulouse.

Work has been done by Alex Corjon at Cerfacs in Toulouse to model the behaviour of vortices in ground effect. The model correctly predicts the motion of vortices over very short periods using a refined version of George Greene's model. Unfortunately, this model still has the drawback that the decay processes are not modelled well, particularly for longer timescales greater than a minute.

2. 3. Work done in the USA.

As stated before a huge number of observations have been made in the USA over the past twenty years or so, of which little has been published. This is largely owing to political circumstances, but Hallock has promised to take on the onerous task of ploughing through the data and publishing the results as soon as it is possible.

2. 4. USA conference in October/November 1996.

A conference on the subject of wake vortices is to be held in the USA, probably in Boston. This conference will be held in the Autumn of 1996 and will be open to all interested parties.

This conference will serve to focus work, and hopefully the plethora of unpublished work will be prepared with this conference in mind.

3. Proposed work for the remainder of 1996.

It is clear that there is a huge amount of interest in the subject of wake vortex research, both commercially and from a safety point of view. It is also a subject that covers many varied disciplines. Because of the diverse nature of these disciplines it is important to maintain contact across the board in order to be in a position to take advantage of any new work from whatever source as well as to deliver any results obtained to the other parties involved as efficiently as possible.

3. 1. Boundary layer meteorology.

One of the principle ways ahead will be to use the results of the methods described in section 1.1.2. There is a good deal to be gained from providing sensible estimates of ε with more than one possible application.

3. 1. 1. Wake vortex database.

As stated earlier, there have been a large number of publications that have attempted to analyse results from this database. Most of the information gleaned has been in relation to aircraft type and other non-meteorological factors. Some work has been done in order to correlate crosswind component to incidents, although it is clear that there is some scope for a more detailed analysis of the meteorological input to the dataset.

3. 1. 1. 1. Verification of incidents.

Woodfield has carried out some work in order to "clean" the dataset; that is to isolate reported incidents that were not likely to have been generated by a wake vortex encounter. His work has largely involved inspection of flight data recorders and specifically uses the record of flight control usage to make deductions about the likely cause of any sudden roll or loss of height.

Having recently received a large sample of incident data it is my intention to use the methods outlined in section 1.2.2. This method has been extended and quantified by Grant[13] in the Meteorological Office and these methods can be used in order to identify reported incidents at the lowest levels that are not likely to have been caused by vortices. Essentially, this means estimating vortex decay and position, and testing whether the relevant aircraft positions are consistent with the theory or not. Owing to the approximations that have been used in these models the number of conclusive results from this work is not likely to be very great.

3. 1. 1. 2. Estimation of hazard criteria.

The work in the previous section will require extreme care so as to ensure that genuine cases are not rejected. This is of vital importance since the same methods can be employed

to estimate levels of vortex strength that do indeed infer a hazardous situation.

Safety cases are required by the CAA whenever operational changes are made to working practices. It has to be demonstrated that levels of safety will not deteriorate as new efficiency measures are introduced. Currently it is accepted that the probability of a fatal accident should be less than $1:10^{-9}$ for any take-off or landing.

This defining of a hazard is a major problem, as to date it has not been done with implications for safety cases. A safety case cannot be quantified in terms of the probability of an accident if the appropriate hazard levels remain undefined. All that has been done so far is to compare safety assessment with current practices on the basis that these procedures are defined as being safe. This is unsatisfactory since the existence of a vortex incident database does tend to refute that argument, but having said that it is widely accepted that the current regulations are generally too conservative.

A more detailed explanation as to how this can be done is listed in section 5.

3. 1. 1. 3. Creation of additional information for the database.

Another task is to use the same methods as previously described to place estimates of turbulence parameters on the database itself. As stated before, this will only be sensible in cases where the height of the encountering aircraft was below around 200 feet. This is because the estimation process involved will not give valid results above this height.

More detailed wind information is also available to the Meteorological Office on some occasions. ASDAR meteorological observational reports are made by some wide-bodied aircraft. These aircraft are unlikely to be encountering aircraft as they are all within the heavy category but some appropriate measurements are likely that would be better estimates than the current estimates that are made with regard to the half-hourly surface observations.

3. 1. 2. Anemometer installation at Heathrow.

As is the case at Orly airport there are four anemometers that will be installed at Heathrow during the summer of 1996 (target is currently mid-June). These are to be installed for ATC purposes, but with some collaboration it is hoped that appropriate logging equipment will be attached so that analysis of short period wind data can be carried out.

It is clear that transportation of vortices is the major mechanism for hazard removal, so the aim is to set up a very short period forecasting method in order to give the appropriate wind velocity predictions with appropriate timescales, and more importantly, the appropriate levels of accuracy.

The level of accuracy would effectively give the size of a "buffer" zone to which the winds can be guaranteed to be within, or at least to give a very high probability of this being the

case. Careful thought needs to be given to turbulence parameters since large variations in wind strength indicate sufficient turbulence so as to cause rapid vortex decay. It is hoped that work from the previous section will allow some quantification of this idea.

It is unlikely that any significant results will come about during 1996 as the supply of data will naturally have some time lag and to produce meaningful statistical results will require a long period of data collection. As a result much of the work will be of a preparatory nature with high emphasis placed on the work in the previous two sections as well as the following section.

3. 1. 3. Consideration of turbulence.

The method described in section 5.1 can be used in order to investigate correlations between the friction velocity (u_*), the Monin-Obukhov length (L) and vortex strength/lifetime. Until now a rather crude evaluation has led to the use of a wind speed, above which it is considered that turbulence would be sufficient to reduce the hazard below acceptable limits. A more detailed study of turbulence itself may well prove valuable.

3. 1. 3. 1. Choice of turbulence parameter.

There are many parameters that can be used, and work is needed in order to establish turbulence parameters that do show high correlations as described in the previous sections. A further parameter has been used in the study of wake vortices and is described by the name "RMS. turbulence". This is simply the standard deviation of mean wind speeds taken over a short averaging period. This parameter will take different values depending on the stability of the atmosphere with these values estimated by taking a proportion of the actual mean wind speed.

As a result the level of stability still requires estimation and therefore this parameter would be difficult to estimate with any degree of confidence. I feel that it would be more profitable to look into the more standard types of turbulence parameter as referred to before.

3. 1. 3. 2. Use of instrumentation.

Laser instruments have been used to measure vortex strength and to observe the tracks of vortices. One such trial took places at Heathrow airport in 1995[10]. It has been suggested by Woodfield that work could be done in order to study such instrument data with a view to obtaining turbulence information. A new measure would be the result, with some extensive checking then required in order to calibrate such measurement. This work could make use of turbulence instruments and expertise at the research centre at Cardington in Bedfordshire.

This will require some preliminary investigation and much thought, and it would certainly be the case that anything operational resulting from such work would be at least two or three years off.

4. Proposed work beyond 1996.

The installation of the anemometers at Heathrow will allow a flow of data that will become more useful beyond 1996 as sample sizes grow. This data would be a major tool in demonstrating the crosswind forecasting possibilities, and much of any work would involve methods of presentation of this data and estimation of forecast accuracy. This accuracy is of vital importance with the use of probability likely to be worthwhile.

4. 1. Heathrow departures.

The departures problem is certainly more tractable with this being the obvious place to attempt a first stage advisory system. Probability forecasts of winds should still be the best approach, although a deterministic approach could well be viable for the shorter forecast periods that are required for departures. It is intended that both should be looked at.

4. 2. Heathrow arrivals.

This would be very much a stage two operation with the use of probabilities a near certainty. By this time it is hoped that some fruitful work on turbulence will enable the generation of a complete system with hazard levels being a little more clearly defined.

5. Technical notes.

The area considered is the limits for total wind speed i.e. a measure of general turbulence.

5. 1. Method of analysing and assessing vortex lifetime/ strength.

Turbulence is of prime importance here; the details below show a standard method by which turbulence parameters can be incorporated into any forecast system. Many of the inputs refer to previous sections, but can be estimated with reasonable accuracy[6], and it is clear that given sufficient data it is possible to estimate hazard criteria and to use such criteria in a forecast system.

Assume that the vortex is described by its circulation (Γ_0) and vortex separation (**b**). From Monin-Obukhov similarity theory the turbulence is described by the friction velocity ($\mathbf{u}_*$), the Monin-Obukhov length (**L**) and height above the ground (**z**).

From the above three independent non-dimensional parameters can be formed.

$$\mathbf{u_* b / \Gamma_0 \ , \ z / b \ , \ z / L.}$$

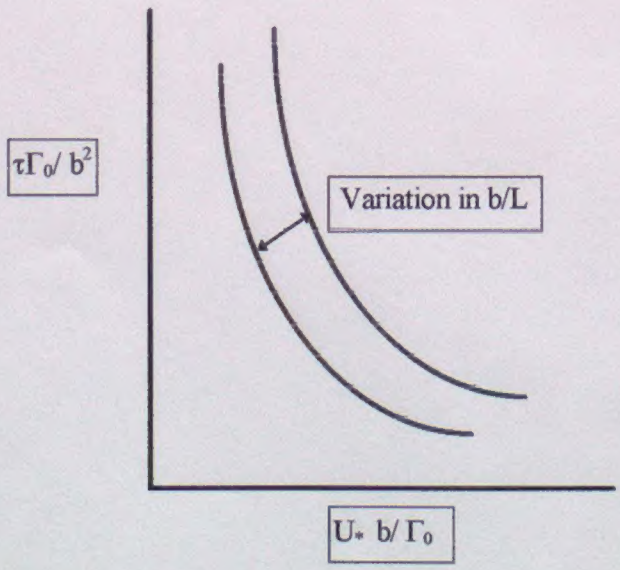
The vortex lifetime (τ) becomes:-

$$\Gamma_0 \tau / b^2 = F\left(u_* b / \Gamma_0 , z/b , z/L \right)$$

Assuming that the vortices are in ground effect, so $\mathbf{z \approx b}$.

$$\Gamma_0 \tau / b^2 = F\left(u_* b / \Gamma_0 , b/L \right)$$

Given suitable data estimates could be derived for minimum values of $\mathbf{u_* b / \Gamma_0}$ which



would give lifetimes sufficient for encounter.

Strength can be analysed in the same way.

$$\Gamma/\Gamma_0 = F\left(t\Gamma_0/b^2, u.b/\Gamma_0, b/L\right), \text{ where } \mathbf{t = time}$$

Given separation vortex strength could be estimated.

6. Brief summary of proposed work.

- To examine the CAA incident database with regard to meteorological conditions, including turbulence. The aim is to highlight events that are unlikely to be vortex related and then to enable the identification of hazard criteria. (1996)
- To analyse data from anemometers at Heathrow from June 1996 with regard to predicting crosswinds with as much accuracy as possible and to create the ability to predict confidence levels of forecast accuracy. (Late 1996 and ongoing)
- To use results from incident database in order to arrive at turbulence forecasts in real time for use with respect to departures from Heathrow. This will be the basis of a wake vortex advisory system. (1997 and ongoing)
- To extend the concept over longer periods with help from synoptic scale forecasts and possibly computer models for use with respect to arrivals at Heathrow. (Late 1997 and ongoing)
- To assist and advise as required on meteorological aspects of any other work being carried out regarding wake vortices. (As required)

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